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# A review of modeling development for estimations of ocean–sea ice–ice shelf interaction in Prydz Bay, East Antarctica

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**Abstract** Prydz Bay, East Antarctica, is a critical region for studying ocean–sea ice–ice shelf interactions and their role in the global climate system. This review synthesizes the advancements in numerical modeling of physical oceanographic processes in Prydz Bay, highlighting the evolution from early one-dimensional thermodynamic models to contemporary high-resolution, three-dimensional coupled ocean–sea ice–ice shelf frameworks. We discuss key milestones in understanding processes such as frazil ice dynamics and its impact on the basal mass balance of the Amery Ice Shelf, the pathways and mechanisms of Modified Circumpolar Deep Water intrusions, and the dynamic influences of large icebergs on regional circulation. Despite significant progress, challenges remain in integrating multi-component interactions and achieving long-term, high-resolution climate projections. Future efforts should focus on developing fully coupled models that incorporate atmosphere–ocean–sea ice–ice shelf–iceberg interactions, supported by enhanced observational networks and improved computational efficiency. This review underscores the importance of continued modeling advancement to better predict the responses of Antarctic ice shelves and polar climate to global change.

**Keywords** **Prydz Bay, modeling development, ocean, sea ice, Amery Ice Shelf**

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## 1 Introduction

The Antarctic region occupies a critically strategic position in the global climate system, regulating the sea ice evolution, atmospheric and oceanic circulations, and carbon sequestration (Rintoul et al., 2018). Moreover, the Antarctic region plays a key role in regulating the global meridional overturning circulation (Lee et al., 2023) and sea-level rising (Chen et al., 2017; Shepherd et al., 2010). Over recent decades, Prydz Bay in East Antarctica has been recognized as a critical region exhibiting intensive ocean–atmosphere–sea ice–ice shelf interactions, conferring significant scientific value and regional representativeness.

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After the Ross Sea and Weddell Sea, Prydz Bay is the third-largest embayment in Antarctica (Figure 1). Bounded by the West Ice Shelf to the west, Davis Sea to the east, and the Amery Ice Shelf (AIS) to the south, Prydz Bay opens northward towards the Indian Ocean sector of the Southern Ocean (60°E–90°E). Featuring diverse water masses (Nunes Vaz and Lennon, 1996), complex circulation structures (Pu et al., 2007), and high biodiversity (Li et al., 2015; Post et al., 2014; Williams et al., 2010), Prydz Bay holds strategic significance for the Chinese National Antarctic Research Expeditions (CHINAREs) and the international Antarctic research enterprise. Since 1984, the 41 CHINAREs have undertaken systematic investigations, designating Prydz Bay as a scientific sentinel for Antarctic research. Within Prydz Bay, the Zhongshan Station was established on the Vestfold Hills in 1989, followed by the Taishan Station in Princess Elizabeth Land in 2014. Functioning as operational springboards, these stations enable the forays of CHINARE into the scientific exploration of Antarctic continental interior. Therefore, comprehensive investigations of ocean–sea ice–ice shelf interactions in Prydz Bay are essential to improve our understanding of the complex polar climate system and its feedback to global climate changes.

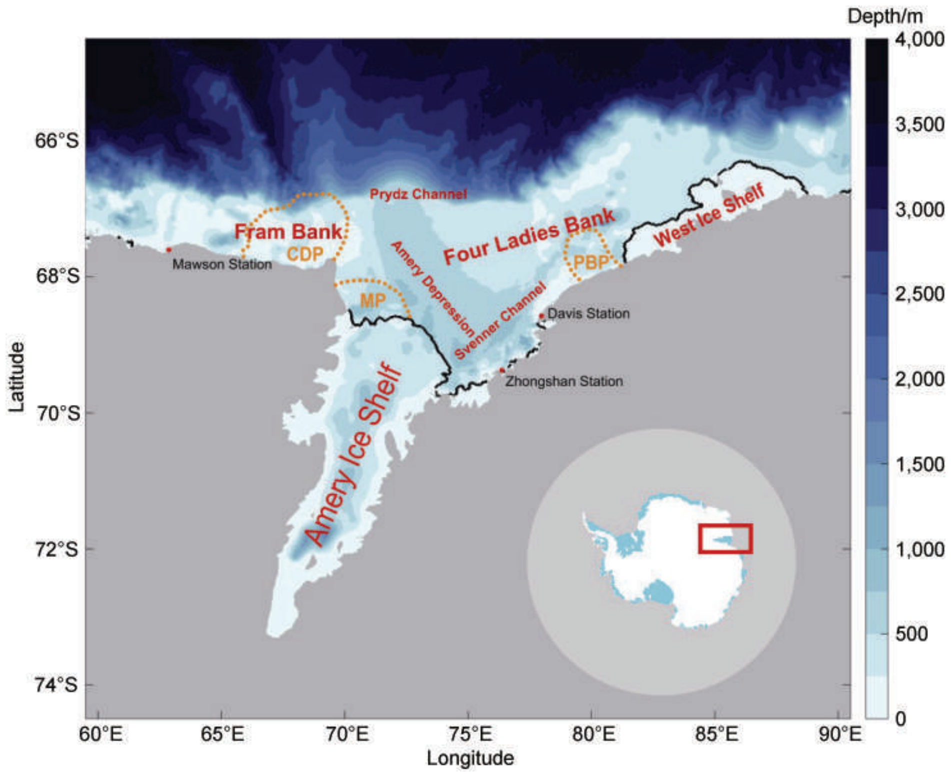


**Figure 1** The water column thickness in Prydz Bay from RTopo-2 (Schaffer et al., 2016). Yellow dashed lines denote the location of polynyas in the austral winter. CDP, Cape Darnley polynya; MP, Mackenzie polynya; PBP, Prydz-Barrier polynya. Red dots denote the locations of expedition stations. The red box in the lower inset shows the location of Prydz Bay.

Prydz Bay constitutes a critical nexus that dynamically links the Antarctic ice sheet, ice shelves, continental shelf, and the Indian Ocean Sector of Southern Ocean (Figure 2). In Prydz Bay, the large-scale circulation is known as the cyclonic Prydz Bay Gyre (PBG), with the inflow over the Four Ladies Bank and outflow along the rim of the Fram Bank (Nunes Vaz and Lennon, 1996; Smith et al., 1984). The westward Antarctic Slope Current (ASC) hugs the northern continental slope, characterized as a Fresh Shelf regime (Thompson et al., 2018). The sea ice fully covers entire Prydz Bay in the austral winter, except a few polynyas remaining open due to katabatic winds, while the sea ice significantly retreats in the austral summer, with a notable seasonal cycle. The AIS, the third-largest Antarctic ice shelf after the Ross and Ronne-Filchner ice shelves, discharges ~16% of East Antarctica's ice flux into the ocean (Allison, 1979). The AIS covers ~62,000 km² (Galton-Fenzi et al., 2008), with its ice draft featuring the deepest grounding line around Antarctica and a maximal depth to ~2,500 m. Accompanied by massive heat and freshwater exchange (Hellmer and Jacobs, 1992; Liu et al., 2017), the basal melting rate of the AIS is up to ~(51.5±9.6) Gt·a$^{-1}$ (Wen et al., 2010), with a maximum of ~30 m·a$^{-1}$ at the deepest grounding zone (Galton-Fenzi et al., 2012). Based on hydrographic observations, previous studies have found that Modified Circumpolar Deep Water (MCDW) and High Salinity Shelf Water can access the sub-ice-shelf cavity of the AIS, directly influencing the oceanic heat content and basal melting/freezing rates of the AIS (Herraiz-Borreguero et al., 2015, 2016). Therefore, the convergence of complex

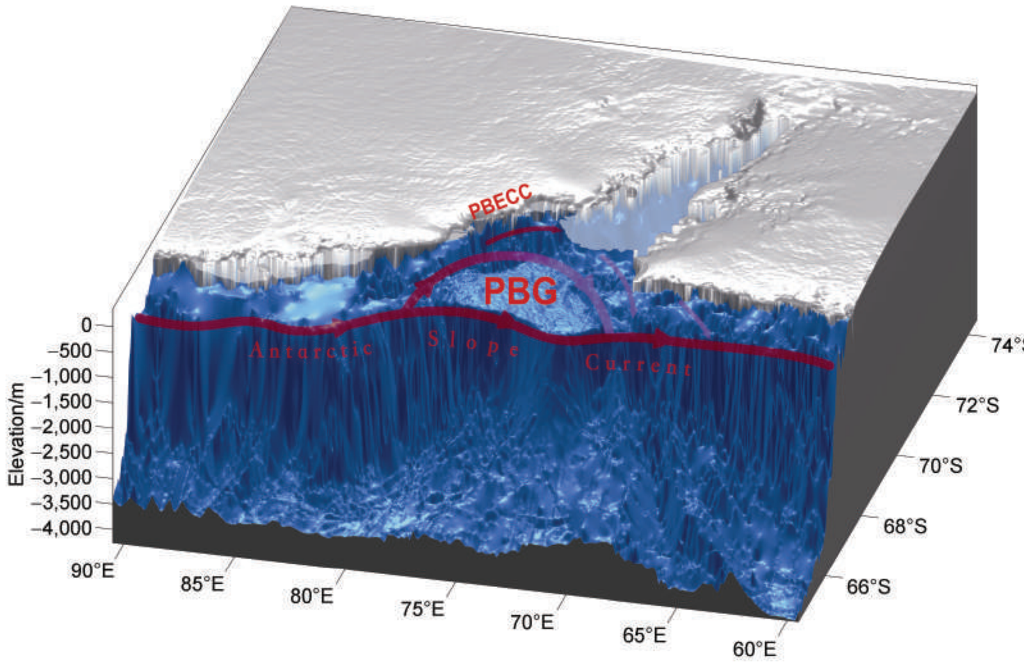


**Figure 2** Large-scale circulations in Prydz Bay, with the geometry derived from RTopo-2. The blue regime represents the seafloor, the white regime represents the ice sheet, and the translucent gray areas represents ice shelves. The red line along the slope shows the position of the Antarctic Slope Current (ASC). Onshore red arrows denote warm intrusion flows over the eastern flank, and offshore purple arrows denote cold outflows in the western flank. PBG, Prydz Bay Gyre; PBECC, Prydz Bay Eastern Coastal Current.

bathymetry, heterogeneous water masses, cross-scale circulation processes, pronounced seasonality of sea ice, and vigorous AIS basal melting/freezing renders Prydz Bay an important window for investigations of the polar climate system.

Research focusing on Prydz Bay and its adjacent seas has expanded considerably over recent decades. Early in-situ observations and theoretical studies documented the fundamental characteristics of water masses, circulation patterns, sea ice properties, and the basal mass balance of ice shelves in Prydz Bay (Allison, 1979; Craven et al., 2004; Gwyther et al., 2020; Herraiz-Borreguero et al., 2016; Middleton and Humphries, 1989; Nunes Vaz and Lennon, 1996; Shi et al., 2011). These pioneering efforts laid the groundwork to establish a baseline understanding of key physical processes. Nevertheless, severe logistical constraints and the extreme polar environment persistently hinder comprehensive data collection. Consequently, the existing dataset is characterized by significant gaps and limitations across different methodologies. While satellite remote sensing provides extensive spatial coverage, its observations are largely confined to surface processes. Ship-based hydrographic surveys, conducted primarily in the summer, yield valuable vertical profiles of the water column but are inherently limited in their temporal resolution and spatial coverage. Moorings can deliver long-term, high-frequency time series, yet their deployment is logistically challenging, resulting in sparse data from a limited number of fixed stations. Most critically, direct observations beneath the ice shelves remain exceptionally scarce due to the formidable technical difficulties of access, leaving the sub-ice-shelf cavity as the most poorly observed domain.

Given the sparsity of observational data, numerical modeling provides crucial insights into ocean–sea ice–ice shelf interactions in Prydz Bay. Numerical models can fill gaps in regions and periods inaccessible to observations and provide a powerful approach to elucidate underlying mechanisms, particularly by simulating mesoscale and submesoscale processes that are difficult to capture with field measurements. Therefore, modeling frameworks not only illuminate otherwise unobservable ocean processes but also are useful to plan future field campaigns. Regional models focused on Prydz Bay has evolved from early simplified thermohaline circulation schematics (Hellmer and Jacobs, 1992) to contemporary three-dimensional ocean–sea ice–ice shelf coupled frameworks (Sun et al., 2022). Such a progression has been marked by continual advances in model resolution, physical process representation, and validation methods. These modeling developments underpin the advanced understanding of the mechanisms governing ocean–sea ice–atmosphere–ice shelf interactions in Prydz Bay.

This review seeks to synthesize the development of numerical modeling for Prydz Bay and outline the evolution and research progress in simulating ocean–sea ice–ice shelf interactions within the bay and its vicinity. Through a comprehensive discussion of critical knowledge gaps and potential future research directions, this work endeavors to offer a theoretical foundation and methodological reference for advancing the future development of multi-sphere coupled modeling frameworks, polar observational deployments, and their application in climate change research.

To chart this development, the review begins by establishing the environmental context and scientific imperatives in Section 2. Section 3 subsequently traces the technical evolution of the numerical models. Building upon this foundation, the major scientific insights derived from applying these models are synthesized in Section 4. Persistent limitations and promising future research pathways are then discussed in Section 5. The review concludes with a synthesis of the main points in Section 6.

## 2 Research frontiers in Prydz Bay

The complex environment of Prydz Bay features distinctive topography, dynamic water masses, and strong seasonal ice regimes which together prioritize several critical processes in ice–ocean interactions. Bathymetric conduits guide warm water onto the continental shelf, extensive sub-ice-shelf cavities host vigorous melt and freeze processes, and recurrent coastal polynyas drive dense shelf water formation. These elements collectively define fundamental yet unresolved scientific questions. Key features including the Prydz Channel and Four Ladies Bank regulate the onshore flow of warm MCDW. Simultaneously, polynyas such as the Cape Darnley polynya serve as essential sites for dense water formation and Antarctic Bottom Water production. As a result, the research frontier has progressively shifted from mapping large-scale patterns to resolving underlying physical mechanisms. The construction of dynamically consistent modeling frameworks focused on warm water intrusion pathways, sub-ice-shelf circulation, sea ice–ocean coupling, and multi-scale energy transfer now represents the primary focus of international research efforts in Prydz Bay.

Clarifying the dynamical mechanisms controlling MCDW intrusion pathways and their sensitivity to climate forcing remains an active research focus (Herraiz-Borreguero et al., 2015, 2016). Current efforts are moving beyond the identification of mean intrusion pathways to clarify the underlying dynamical mechanisms regulating onshore warm deep water intrusion. The primary research objective is to elucidate how these dynamics control the variability and intensity of heat delivery onto the continental shelf. A key priority is determining the sensitivity of these intrusion dynamics to climate modes such as the Southern Annular Mode, which may alter wind forcing and remote oceanic anomalies, ultimately affecting heat delivery to the AIS front and modulating basal mass balance. Such research not only helps reveal how heat sources propagate from the deep ocean to the sub-ice-shelf cavity but also provides a physical basis for predicting future stability of the AIS under climate warming scenarios.

Elucidating the role of frazil ice and marine ice accretion in regulating ice–ocean feedbacks beneath the AIS remains a central challenge (Craven et al., 2009; Fricker et al., 2001). While recent studies have emphasized the influences of frazil ice, a mechanistic understanding of how supercooling, frazil formation, and boundary layer mixing interact to regulate the basal mass balance of the AIS is still evolving. Current efforts focus on quantifying the feedback between frazil ice transport, marine ice deposition, and the modification of heat and freshwater fluxes near the ice base. Understanding these processes is essential for the models to accurately represent the phase change and energy transfer mechanisms that govern melting and freezing regimes under the AIS.

Understanding the coupled interactions between sea ice evolution, dense shelf water formation, and iceberg-induced circulation changes in Prydz Bay remains a critical challenge (Ohshima et al., 2013; Yang et al., 2016). The heat flux between the sea ice and ocean significantly influences seasonal growth and melt of the landfast sea ice, yet such key processes still require further refinement in models. Major efforts are focused on quantifying the mechanisms of dense shelf water production in coastal polynyas and its subsequent export, which contributes to Antarctic Bottom Water formation. At the same time, the persistent presence of large grounded icebergs introduces complex perturbations to regional currents and hydrography. These icebergs alter the pathways of major currents such as the ASC and the Prydz Bay Eastern Coastal Current (PBECC), modify local water mass properties, and ultimately influence heat transfer toward ice shelf cavities. A central research priority involves integrating these complex interactions among sea ice, polynya activity, iceberg effects, and shelf water transformations into coupled dynamic and thermodynamic frameworks to better assess their collective impact on regional climate and the stability of the AIS.

Quantifying the influences of tides and mesoscale and submesoscale eddies is still a challenge in understanding the dynamics of cross-slope exchange in Prydz Bay (Liu et al., 2025; Stewart et al., 2018). Current research focuses on quantifying how tide-driven and eddy-driven transports collectively regulate onshore heat flux, particularly the degree to which tidal processes may compensate for the eddy-dominated transport across the continental slope in Prydz Bay. A key point concerns how the instabilities of the ASC actively modulate the thermohaline structure of the Antarctic Slope Front (ASF) and cross-slope exchanges. Research therefore prioritizes the development of models capable of resolving non-linear interactions between tides, mesoscale and submesoscale eddies, and the mean flow to better quantify their combined role in the regional heat and salt budget.

Overall, these research frontiers underscore the important role of Prydz Bay as a natural laboratory for addressing fundamental questions in polar oceanography.

Resolving the complex interactions involving MCDW intrusions, ice shelf basal processes, sea ice-ocean feedbacks, iceberg impacts, and multi-scale ocean energetics remains essential to advance the predictive understanding of the polar climate system.

# 3 The development of numerical models in Prydz Bay

Numerical modeling has evolved into a cornerstone methodology for investigating ice–ocean interactions in Prydz Bay, with its technical development marked by substantial advances in physical representation, spatial resolution, and process coupling. Early modeling efforts were constrained to relatively simplified frameworks, even limited to one-dimensional thermodynamic simulation. Progress in computational capacity and numerical techniques has enabled a systematic expansion in model capabilities, facilitating the integration of complex dynamics. Simulations have advanced from one-dimensional vertical column models to high-resolution three-dimensional configurations that incorporate key components such as frazil ice microphysics, thermodynamically active ice shelves, and tides. These developments have allowed for the emergence of multi-component coupled systems that more realistically represent feedbacks across the ocean, sea ice, and ice shelves. Despite the persistent burden of computational demands, these advancements in numerical modeling have not only refined the representation of regional oceanography and ice dynamics but have also established a foundational toolkit for probing climate sensitivity and ice shelf stability in Prydz Bay and beyond.

## 3.1 Evolution of model sophistication

Using a multilayer thermodynamic sea ice model combined with atmospheric forcing data and sea ice thickness measurements, Heil et al. (1996) simulated the growth of landfast sea ice near the Mawson Station in Prydz Bay from 1958 to 1986, and solved the oceanic heat flux via the energy balance equation. The Helsinki Institute of Technology Sea Ice model (HIGHTSI), a one-dimensional model, is suitable for the investigation of the coastal landfast ice region where the horizontal heat transport is negligible. With the aid of the HIGHTSI, Yang et al. (2016) has studied the heat transfer at the ice–ocean interface during the sea ice growth period in Prydz Bay. The HIGHTSI successfully reconstructed seasonal thickness variations of the landfast ice in Prydz Bay, and Yang et al. (2016) further analyzed the roles of oceanic vertical heat flux and the sea ice albedo in influencing the ice thickness. Although the HIGHTSI cannot resolve dynamic processes of sea ice or the influences of oceanic horizontal transport, it is structurally simple and facilitates sensitivity analyses and parameter calibration.

A two-dimensional thermohaline circulation model (Hellmer and Olbers, 1989) was introduced to investigate the influences of the AIS geometry on the sub-ice-shelf circulations and marine ice formation. By varying the basal ice shelf morphology and the seafloor bathymetry, Hellmer and Jacobs (1992) conducted sensitivity experiments to identify the cavity geometry that best reproduced observed oceanographic conditions beyond the ice shelf front. Barotropic tidal models are two-dimensional gravity wave models that are computationally efficient for investigating the tidal propagation and energy dissipation. Hemer et al. (2006) used a barotropic tidal model to assess the sensitivity of oceanographic properties in the AIS cavity to tidal forcing, and Maraldi et al. (2007) used a tidal model to reproduce principal tidal constituents in the Indian Ocean sector, including the AIS. Although two-dimensional models can not represent three-dimensional dynamics, these models provide valuable insights into topographic controls on oceanic currents and ice-ocean interactions.

Three-dimensional models, including the inverse model (Liang et al., 1993), have been widely used to simulate the ocean, sea ice, and ice shelves in Prydz Bay. Shi et al. (2000a, 2000b) used a three-dimensional ocean-solo model to simulate the spatial and temporal features of circulations in Prydz Bay. Williams et al. (2001, 2002) were the first to employ a three-dimensional ocean–ice shelf coupled model to simulate the interactions between ocean and the AIS. Using the Massachusetts Institute of Technology General Circulation Model (MITgcm), Li et al. (2011) developed a regional coupled ocean–sea ice model to study the seasonality of sea ice and the three typical coastal polynyas in Prydz Bay. Based on the Regional Ocean Modeling System (ROMS), Galton-Fenzi et al. (2012) studied the circulation in the marine ice accretion in the AIS cavity. With the aid of the MITgcm, Liu et al. (2017, 2018) developed a regional coupled ocean–sea ice–ice shelf model to study the intrusion pathways of MCDW from the deep ocean to the AIS cavity. Similarly, Wu et al. (2021) used the same model to quantitatively analyze the Lorenz energy cycle in the AIS cavity. These three-dimensional models not only reproduce dynamic and thermodynamic fields of the ocean and sea ice but also provide insights into the underlying mechanisms governing the ocean–sea ice–ice shelf interactions.

The development of dedicated models for distinctive phenomena in Prydz Bay substantially advances our understanding of their dynamics and controlling mechanisms. For example, both remote sensing and local hot-water drills have revealed extensive suspended marine ice beneath the AIS (Budd et al., 1982; Craven et al., 2009; Fricker et al., 2001; Morgan, 1972). The formation, transport, and accretion of frazil ice act to cement adjacent ice streams and enhance ice shelf stability (Holland et al., 2009). By incorporating a frazil ice model introduced into ROMS, Galton-Fenzi et al. (2012) found that the growth and aggregation of frazil crystals within supercooled water layers play a significant role in driving marine ice accumulation. Similarly, Cheng et al. (2020) developed a vertical one-dimension ice shelf–ocean boundary layer model with a frazil ice module to investigate its influences on vertical stratification. Therefore, these studies highlight the importance of developing specialized modeling approaches to unravel the certain distinctive processes in Prydz Bay.

### 3.2 Refinements in model configuration

The performance of numerical models heavily relies on the spatial resolution and the accuracy of bathymetry. The evolution of modeling capabilities in Prydz Bay is marked by a clear trend toward increased spatial resolution, which has progressively enabled the explicit representation of finer-scale processes. Galton-Fenzi et al. (2012) pioneered the simulation of three-dimensional ocean–ice shelf coupling with an average resolution of 5 km. Building on this, Liu et al. (2017) established the first fully coupled ocean–sea ice–ice shelf model of Prydz Bay at a higher resolution of 1.5 km. Recently, Liu et al. (2022) employed an even finer grid spacing of 500 m in a process-oriented idealized setup to explicitly resolve cross-slope exchange dynamics in Prydz Bay. This steady enhancement in spatial resolution is instrumental in directly simulating submesoscale and mesoscale processes and greatly improving our understanding of the physical mechanisms and influences.

The refinement of bathymetric and ice shelf cavity data is important in advancing the realism simulations of Prydz Bay. Hellmer and Jacobs (1992) employed a two-dimensional thermohaline model to indirectly infer the AIS cavity geometry through sensitivity experiments, adjusting the morphology until simulated hydrographic results roughly matched sparse observations. Based on a tidal model, Galton-Fenzi et al. (2008) tuned the seafloor depth beneath the AIS to achieve consistency between simulated and observed tidal elevations, thereby producing an improved three-dimensional representation of the sub-ice-shelf cavity. With the advent of extensive airborne ice-penetrating radar surveys and ocean bathymetric mapping, the development of standardized topographic products such as the RTopo-1 (Timmermann et al., 2010) and RTopo-2 (Schaffer et al., 2016) datasets has provided increasingly accurate and observationally constrained topographic conditions (Liu et al., 2017, 2018). Furthermore, Sun et al. (2022) corrected the bathymetry in Prydz Bay using hydrographic data and conducted sensitivity experiments, and Sun et al. (2022) revealed that the refined topography significantly altered the circulations over the continental shelf and reduced the onshore heat transport. Consequently, the basal melt rate of the AIS decreased by ~13%, while that of the West Ice Shelf increased due to localized warming. These high-resolution topographic datasets have become indispensable for modern modeling efforts, allowing for a more faithful reproduction of shelf circulation dynamics and ice–ocean interactions in Prydz Bay.

### 3.3 Improving model validation through enriched observations

Rigorous validation of numerical models against comprehensive and diverse observational datasets is essential for assessing their performance in simulating the complex climate system in Prydz Bay. The harsh polar environment and logistical challenges have historically resulted in sparse observational data in Prydz Bay. However, technological advances have significantly expanded the temporal coverage, spatial range, and diversity of these datasets over time. Ship-based hydrographic surveys conducted by research icebreakers provide temperature, salinity, and current profiles along some important cross-sections in Prydz Bay (e.g., hydrographic transect surveys from the CHINAREs), although these observations are largely limited to the summer season. Complementing these broad-scale snapshots, moorings deployed in the bay and hot-water drilling sites on the AIS supply valuable long-term records of thermohaline properties and currents at fixed locations (e.g., mooring and borehole observations from the Amery Ice Shelf Ocean Research project). The satellite era has further expanded the scope of monitoring by enabling continuous basin-scale observations of sea surface temperature, sea surface height, and sea ice concentration (e.g., satellite observations from the National Snow and Ice Data Center, USA), though these are restricted to the surface layer. More recently, animal-borne oceanographic sensors have greatly enriched the hydrographic database (e.g., the Marine Mammals Exploring the Oceans Pole to Pole observations), particularly by delivering unprecedented wintertime data that are otherwise inaccessible to ship-based campaigns.

## 4 Milestones in understanding from numerical simulations

Over recent decades, by bridging spatial and temporal observational gaps, numerical modeling has served as an important tool in unraveling key processes governing ocean–sea ice–ice shelf interactions in the Prydz Bay region. We synthesize several fundamental advances achieved through numerical studies, focusing on the role of frazil ice in modulating the basal mass balance of the AIS, the pathways and dynamics of MCDW intrusions onto the continental shelf, and the profound dynamic influences caused by large icebergs. Together, these contributions mark significant milestones in understanding the complexity and sensitivity of the marine environments in Prydz Bay.

### 4.1 Impact of frazil ice on the AIS basal mass balance

The formation and dynamics of frazil ice represent one of the key physical mechanisms influencing ice shelf basal mass balance. Early studies have shown that Ice Shelf

Water becomes supercooled during its ascent due to decreasing pressure, thereby promoting frazil ice formation (Jenkins and Bombosch, 1995; Smedsrud and Jenkins, 2004). These ice crystals can either remain suspended in the water column or accumulate at the base of the ice shelf as marine ice, significantly altering thermohaline exchange and ice shelf stability.

Galton-Fenzi et al. (2012) for the first time incorporated the frazil ice dynamics into the ROMS that is also coupled with tidal forcing with updated AIS cavity geometry. The study revealed that frazil ice primarily forms in the supercooled layer near the ice shelf base, with a net accumulation rate of 5.3 $Gt \cdot a^{-1}$ that comprises 3.7 $Gt \cdot a^{-1}$ from frazil ice adhesion and 1.6 $Gt \cdot a^{-1}$ from direct basal refreezing. The presence of frazil ice not enhances marine ice accretion but also modifies the salinity and buoyancy of Ice Shelf Water through salt release, consequently influencing the sub-ice-shelf circulation structure and heat flux distribution. Although premature settling led to a slightly more southerly distribution of marine ice in the simulations, the model still showed good agreement with observations in both magnitude and spatial pattern of the marine ice distribution, underscoring the importance of frazil ice processes in the basal mass balance of the AIS. The study further supports the potential effect of frazil ice on ice shelf stability (Holland et al., 2009) and emphasizes that incorporating dynamic frazil ice modules into future coupled ocean–sea ice–ice shelf models is essential for accurately predicting responses of the AIS to climate change.

## 4.2 Pathways of MCDW intrusion

The intrusion of MCDW has profound implications for the basal melt of the AIS (Herraiz-Borreguero et al., 2015, 2016). As a relatively warm water mass, the upwelling of MCDW from the deep ocean onto the continental shelf and its subsequent access into ice shelf cavities can significantly enhance the basal melt rates. Since the AIS is the third largest and the deepest ice shelf in Antarctica, accurately understanding the pathways and mechanisms of MCDW intrusion are crucial for predicting the response of AIS to climate change and its contribution to sea level rise.

Based on the MITgcm, Liu et al. (2017) developed an eddy-resolving regional ocean–sea ice–ice shelf coupled model to identify, for the first time, two critical windows for MCDW intrusion in Prydz Bay. The first is via the eastern branch of the cyclonic PBG, which transports MCDW to the AIS calving front, accounting for an annual mean heat transport of $8.7 \times 10^{11}$ $J \cdot s^{-1}$. The second pathway is located east of the Four Ladies Bank, where MCDW is channeled through submarine troughs and conveyed by the PBECC to the eastern flank of the AIS, with a larger annual mean heat transport of $16.2 \times 10^{11}$ $J \cdot s^{-1}$. Furthermore, the study highlighted the substantial role of mesoscale eddies, contributing 23% and 52% to the total onshore heat transport via the PBG and PBECC pathways, respectively. This underscores the critical role of the dynamic effects of topography on the ASC in regulating cross-shelf exchanges (Klinck and Dinniman, 2010; St-Laurent et al., 2013).

## 4.3 Dynamic mechanism governing MCDW intrusion

Understanding the dynamic mechanisms governing the intrusion of MCDW onto continental shelf in Prydz Bay is critical for predicting the stability of the AIS and global sea-level rise (Pritchard et al., 2012; Rignot et al., 2013). The ASC and the associated ASF act as a barrier to MCDW intrusion, yet topographic features such as submarine troughs facilitate cross-shelf exchanges (Herraiz-Borreguero et al., 2015; Silvano et al., 2019). Investigating the processes that enable MCDW to bypass the ASC/ASF is essential for improving climate models and projecting future changes in the Antarctic Ice Sheet.

Liu et al. (2022) employed an idealized eddy-resolving coupled ocean-ice shelf model to clarify three dynamic mechanisms driving MCDW intrusion in submarine troughs over East Antarctica. First, the bottom pressure torque dominates the time-mean onshore flow; second, the Topographic Beta Spiral controls the vertical structure of the inflow; third, topographic Rossby waves induce high-frequency oscillations in onshore volume and heat transport. Liu et al. (2022) further revealed that MCDW intrusion exhibits a distinct seasonal cycle that peaks in March, which lead three months to the maximum transport of the ASC due to the stratification changes modulating the Topographic Beta Spiral structure. These mechanisms collectively explain observed intrusions in Prydz Bay, aligning with hydrographic observations (Herraiz-Borreguero et al., 2015; Williams et al., 2016), and Liu et al. (2022) provided a dynamical framework for understanding cross-slope exchanges across the convolute isobaths.

## 4.4 Dynamical impacts of giant icebergs

The giant icebergs on Antarctic shelf seas have notable dynamical impacts on the polar climate system. Icebergs, especially when grounded, act as major obstacles that can redirect currents, modify water mass properties, and alter the distribution of sea ice (Grosfeld et al., 2001; Robinson and Williams, 2012). Such processes have remarkable effects on the formation of polynyas and the ventilation of shelf waters. Given the increased iceberg calving rates under ongoing climate warming, quantifying their hydrodynamic influence is essential for improving coupled climate models and predicting the response of the AIS to global change.

The numerical investigation by Han et al. (2022) represents a significant advancement in understanding the dynamic interactions between grounding icebergs and regional ocean circulation in Prydz Bay. Han et al. (2022) employed a high-resolution ROMS configuration to quantify the effects of two giant grounded icebergs (D15 and B15) on the summer circulation in Prydz Bay. Major findings in Han et al. (2022) revealed that iceberg D15, persisting near the West Ice Shelf, disrupts the coastal pathway of the ASC, diverting its flow and strengthening the PBECC while reducing total volume transport. In contrast, the shorter-term grounding of B15 on Four Ladies Bank constricts and redirects the inflow near Prydz Channel, leading to a more concentrated and westward-shifted outflow along the Fram Bank. This study provides the first detailed numerical evidence of how iceberg grounding location and duration differentially reshape circulation patterns in Prydz Bay, with implications for the intrusion of MCDW and the basal melt of the AIS. In addition, Han et al. (2022) underscored the necessity of incorporating realistic iceberg geometry and grounding processes into regional ocean models to accurately simulate shelf dynamics.

# 5 Persistent challenges in future Prydz Bay modeling

Current modeling efforts face numerous challenges, particularly concerning the integration of multi-scale processes, observational data gaps, model coupling capabilities, and the simulation of long-term climate responses. Breakthroughs in these areas are urgently needed.

## 5.1 Towards integrated multi-component coupling

A primary challenge in advancing Prydz Bay modeling lies in the transition from studying isolated processes to achieving integrated multi-component simulations. While significant progress has been made in incorporating individual mechanisms, such as frazil ice dynamics (Cheng et al., 2020; Galton-Fenzi et al., 2012), tidal mixing (Hemer et al., 2006), and mesoscale eddies (Zhang et al., 2022), these elements are often added incrementally or studied under idealized conditions. However, these processes do not operate in isolation but interact synergistically in the natural environment. For instance, frazil ice formation influences and is influenced by oceanic turbulence and boundary layer structure. Tidal currents modulate the energy dissipation and mixing that affect eddy generation, and mesoscale eddies redistribute heat and salt and thereby set background conditions for ice–ocean interactions.

So far, to our knowledge, few models can simultaneously represent these cross-process interactions at appropriate scales. The key mechanical processes such as ice shelf fracture, calving, and basal crevasse evolution remain poorly represented in existing models, limiting our understanding of the climate system in Prydz Bay. Future efforts are necessary to prioritize the development of unified frameworks that capture the complex feedbacks between ice, ocean, and atmosphere, with high-resolution to represent multi-scale processes. Such frameworks must not only incorporate ocean, sea ice, ice shelf, and atmospheric components, but also reproduce the processes of frazil ice, tides, and grounded icebergs.

## 5.2 Towards larger-scale and long-term projections

A limitation in current modeling of Prydz Bay is the predominant focus on short-term integrations, typically confined within the satellite era, which fails to capture the full spectrum of climate-scale variability and feedback processes. Decadal and multi-decadal oscillations, such as those associated with the Southern Annular Mode and El Niño–Southern Oscillation, exert strong influences on regional wind patterns, oceanic heat delivery, and sea ice distribution over shelf seas around Antarctica (Gillett et al., 2006; Yuan, 2004). Yet, the inability of most models to perform centennial simulations at eddy-permitting resolutions severely limits understanding of low-frequency ocean–sea ice–ice shelf interactions and threshold behavior in the polar climate system.

To address this gap, future modeling development should emphasize the long-term integration of high-resolution models enabled by advances in both model ability and computational efficiency. To construct models that are not only physically comprehensive but also computationally feasible, the goal requires continuously efforts devoted into the development of model strategy in polar regions. Such simulations are essential to quantify the sensitivity of oceanography and ice shelves to evolving climatic forcing, especially for climate changes in the Southern Ocean (Schmidtko et al., 2014). Furthermore, model credibility is further established through validation against both observations from both the satellite era and the pre-satellite period, which provide critical benchmarks for assessing simulated variability over longer timescales. Through a combination of prolonged simulations and multi-source data calibration, models can reliably project the evolution of Prydz Bay under changing climate conditions.

# 6 Synthesis and conclusion

As a critical region of ocean–sea ice–ice shelf interactions in East Antarctica, Prydz Bay has been the focus of extensive numerical modeling efforts over the past decades. This review has synthesized the development of numerical models in Prydz Bay, from early one-dimensional thermodynamic frameworks to state-of-the-art coupled ocean–sea ice–ice shelf models. These advancements have significantly enhanced our understanding of key physical processes, including frazil ice dynamics, MCDW intrusion pathways, topographic influences on cross-slope exchanges, and the dynamical impacts of giant icebergs.

The evolution of modeling capabilities has enabled researcher communities to address previously intractable questions regarding the basal mass balance of the AIS, the mechanisms of warm water intrusion, and the role of mesoscale and tidal processes in modulating cross-slope exchanges. Notably, the incorporation of frazil ice microphysics, refined bathymetric and cavity geometries, and the explicit representation of eddies and tides have marked significant milestones in model skill.

This technical progression signals a series of deep paradigm shifts in the approach to polar modeling. Advances in modeling have transitioned the focus from thermodynamic equilibrium to dynamics-dominated processes; from isolated system components to fully coupled interactions and feedbacks; and from idealized geometries to high-fidelity, observationally constrained configurations. These technical advances greatly enhance our ability to accurately simulate the climate changes in Prydz Bay.

Despite these advances, significant challenges remain. A primary limitation is the lack of integrated models that simultaneously represent multi-component interactions among ocean, sea ice, ice shelves, atmosphere, and icebergs at appropriately high resolutions. Furthermore, the scarcity of observational data, particularly beneath ice shelves and during winter months, continues to limit model validation and refinement. Long-term simulations remain computationally prohibitive, limiting our understanding of low-frequency variability and tipping points in Prydz Bay.

Future efforts should prioritize the development of high-resolution coupled models that incorporate atmosphere-ocean–sea ice–ice shelf–iceberg interactions. Enhanced observational networks, including autonomous platforms, animal-borne sensors, and improved remote sensing, are essential to provide the data needed for model initialization, validation, and process understanding. Additionally, efforts to improve computational efficiency will be crucial for enabling centennial-scale simulations at eddy-resolving resolutions.

In summary, numerical models have fundamentally advanced our knowledge of Prydz Bay. With further technological and conceptual progress, numerical models will continue to illuminate complex polar processes and contribute to more accurate projections of polar climate system and global climate feedbacks.

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